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There is a limited knowledge concerning energy requirements of the elderly, especially the oldest old (> 80 years). Energy requirements should be estimated from measurements of energy expenditure. For this purpose twenty-one free-living individuals (eight males, thirteen females) aged 91–96 years living in Göteborg, Sweden were studied. Total body water (TBW) measured by the doubly-labelled-water (DLW) technique was 29·5 (SD 5·4) kg in females and 35·6 (SD 4·3) kg in males. TBW measured using bioelectric impedance (BIA) was 31·6 (SD 6·4) kg in females and 42·0 (SD 7·4) kg in males. The mean difference between TBW measured by BIA and that measured by DLW was 3·54 (SD 3·6) kg ($P = 0·0002$). Resting metabolic rate (RMR) was measured using a ventilated-hood system and averaged 5·36 (SD 0·71) MJ/d in females (*n* 12) and 6·09 (SD 0·91) MJ/d in males (*n* 8). Difference between measured RMR and predicted BMR (*n* 20) was 0·015 (SD 0·86) MJ/d (NS). Total energy expenditure (TEE) measured by DLW averaged 6·3 (SD 0·81) MJ/d in females and 8·1 (SD 0·73) MJ/d in males. Activity energy expenditure (TEE − RMR), thus including diet-induced thermogenesis (DIT), averaged 0·95 (SD 0·95) MJ/d in females (*n* 12) and 2·02 (SD 1·13) MJ/d in males. Physical activity level (TEE/BMR) averaged 1·19 (SD 0·19) in females and 1·36 (SD 0·21) ($P = 0·08$) in males. If DIT is assumed to be 10 % of the TEE, energy spent on physical activity will be very low in this population.

Energy expenditure: Doubly-labelled water: Old age

The elderly are a growing section of the population in Sweden and most Western countries (Landstingsförbundet, 1996) and they are also reaching ever-increasing ages. There is limited knowledge concerning energy requirements of the elderly, especially the oldest old (> 80 years of age) compared with other age-groups. In general, energy requirements appear to decrease with ageing. This reduction depends on:

(1) reduced BMR due to loss of fat-free mass (FFM) with age (Shock *et al*. 1963; McGandy *et al*. 1966; Steen, 1988; Roberts *et al*. 1995). However, the decrease in BMR cannot be explained fully by the loss of fat-free mass (FFM) (Pannemans *et al*. 1995; Roberts *et al*. 1995; Poehlman, 1996), suggesting that other physiological factors may contribute to the reduction of BMR with age (Fukagawa *et al*. 1990);
(2) reduction of physical activity (McGandy *et al*. 1966). The major cause of total energy expenditure (TEE) reduction is the decrease in physical activity (Shock, 1972). Recent studies have confirmed that age is a negative predictor of TEE and especially of activity energy expenditure (AEE) (Black *et al*. 1996).

Energy requirements should be estimated from measurements of energy expenditure (EE). In recent years the doubly-labelled water technique (DLW) (Coward & Cole, 1991) has been widely used for measurement of TEE (Black *et al*. 1996) because of its sensitivity and accuracy. It is considered as the reference method for measurement of TEE in free-living individuals. The method is non-invasive and acceptable to most subjects. However, its use is restricted by high costs and limited availability of the stable oxygen isotope. AEE constitutes the difference between TEE and resting metabolic rate (RMR) and expresses the proportion of the EE spent on physical activity plus diet-induced thermogenesis. Physical activity level (PAL; TEE/BMR) could be used as a relative index of physical activity for comparison with other groups (Black *et al*. 1996).

Abbreviations: AEE, activity energy expenditure; BW, body weight; DLW, doubly-labelled water; EE, energy expenditure; FFM, fat-free mass; PAL, physical activity level; RMR, resting metabolic rate; TBW, total body water; TEE, total energy expenditure.

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The aim of the present study was to measure RMR and TEE in 91–96-year-old subjects and define AEE and PAL.

Materials and methods

Population

Twenty-one individuals (eight males, thirteen females), 91–96 years of age, living in Göteborg, Sweden were studied. They were all free- and independently-living and able to participate, and termed healthy. However, all subjects were living a quiet life. Some of them had not been out of doors for years. Height, body weight (BW), BMI, total body water (TBW), FFM and fat mass are shown in Table 1.

Participants were partly recruited from survivors in a systematic sample of 1148 70-year-old individuals in Gothenburg who had been followed longitudinally since 1971. Sample characteristics have been reported elsewhere (Rinder *et al*. 1975; Steen *et al*. 1993). At the latest follow-up at age 95 years in 1996–7 all 95-year-old individuals in Göteborg were invited to participate (*n* 235). Of those invited to participate, 141 individuals underwent a medical examination, and within that group seventeen individuals who fulfilled the inclusion criteria to be mentally healthy and > 90 years also agreed to participate in the present part of the study.

In addition, four individuals also fulfilling the inclusion criteria were recruited from another population study, the Johanneberg study, which comprised all individuals 70 years of age and over (*n* 340) living in a geographically well-defined area in Göteborg (Rothenberg *et al*. 1993; Augustsson *et al*. 1994).

Total energy expenditure

The principle of the method involves enriching the body water with isotopes of both hydrogen (^2H) and of oxygen (^{18}O) and then determining the washout kinetics of both isotopes as their concentrations decline exponentially towards natural abundance (pre-dose) levels. TEE was measured over 15 d. After collection of a baseline urinary sample, each subject ingested a weighed oral dose of ^2H_2O and $H_2{}^{18}O$. The dosage calculation was based on TBW, estimated by the bioelectric impedance (BIA) technique (BIA-101 equipment; RJL System Inc., Detroit, MI, USA), in order to create a ^2H excess of 150 ppm and an ^{18}O excess of 300 ppm. Urinary samples were taken in the morning and in the evening, 1, 8 and 15 d after drinking the isotopes. Samples were then stored at −20°C until analysed. Isotopes were measured in urine using isotope-ratio MS (Aqua Sira; VG Isogas Ltd, Middlewich, Ches., UK), and CO_2 production was calculated from isotope ratios for samples at baseline and at 1, 8 and 15 d using the equation of Schoeller, as described by Westerterp *et al*. (1995*b*). CO_2 production was converted to EE using a RQ of diet of 0·85. Values for disappearance rates for hydrogen (^2H) and oxygen (^{18}O) and dilution space ratio (dilution of ^2H: dilution of ^{18}O) for individuals are given in Table 2.

Table 1. Height (Ht), body weight (BW), BMI, total body water (TBW), fat-free mass (FFM) and fat mass (FM) of free-living Swedish subjects aged 91–96 years*

				TBW (kg)		FFM (kg)		FM (kg)	
Subject no.	Ht (m)	BW (kg)	BMI (kg/m^2)	DLW	BIA	DLW	BIA	DLW	BIA
Females									
1	1·60	41·0	16·0	24·6	26·6	33·7	36·4	7·3	4·6
3	1·55	62·0	25·8	24·8	27·8	34·0	37·9	28·0	24·1
4	1·50	56·0	24·9	26·0	27·7	35·6	37·9	20·4	18·1
5	1·64	63·4	23·6	29·8	32·3	40·8	44·2	22·6	19·2
7	1·50	72·3	32·1	31·5	30·3	43·1	41·5	29·2	30·8
8	1·52	46·7	20·2	24·9	27·7	34·1	37·9	12·6	8·8
10	1·61	55·7	21·5	26·8	27·3	36·7	37·4	19·0	18·3
11	1·56	53·0	21·8	28·3	30·3	38·8	41·5	14·2	11·5
15	1·67	80·0	28·7	35·2	34·3	48·2	47·0	31·8	33·0
16	1·56	56·7	23·3	25·6	28·1	35·1	38·5	21·6	18·2
17	1·52	63·0	27·3	27·6	29·4	37·8	40·2	25·2	22·7
19	1·73	61·0	20·4	37·8	41·0	51·8	56·2	9·2	4·8
21	1·72	86·0	29·1	41·4	48·6	56·2	66·6	29·8	19·4
Mean	1·59	61·3	24·2	29·5	31·6	40·4	43·3	20·8	17·9
SD	0·08	12·5	4·4	5·4	6·4	7·3	8·8	8·0	8·8
Males									
2	1·72	64·0	21·6	30·8	36·7	42·2	50·3	21·8	13·7
6	1·73	69·0	23·1	37·1	41·5	50·8	56·8	18·2	12·2
9	1·69	70·0	24·5	38·9	42·8	52·9	58·6	17·1	11·4
12	1·70	53·6	18·5	33·0	39·0	45·2	53·4	8·8	0·6
13	1·65	70·0	25·7	33·5	35·5	45·9	48·6	24·1	21·4
14	1·76	79·6	25·7	44·2	58·9	44·2	80·7	35·4	−1·1
18	1·70	65·0	22·5	34·3	43·7	47·0	59·9	18·0	5·1
20	1·65	66·0	24·2	33·2	38·0	45·5	52·1	20·5	13·9
Mean	1·70	67·2	23·2	35·6	42·0	48·8	57·6	18·3	9·6
SD	0·04	7·3	2·4	4·3	7·4	5·9	10·2	4·7	7·6

DLW, doubly-labelled-water method; BIA, bioelectric impedance technique.
* For details of subjects and procedures, see pp. 320–322.

Table 2. Doubly-labelled water data for the free-living Swedish subjects aged 91–96 years*

Subject no.	$^{2}H_2O$ (‰) Baseline	Day 1	Day 15	$H_2{}^{18}O$ (‰) Baseline	Day 1	Day 15	$D_H:D_O$
Females							
1	149·5	301·3	188·9	2000·8	2281·9	2054·7	1·007
3	148·5	306·0	206·7	1997·8	2292·7	2080·5	1·045
4	148·2	297·8	203·8	1997·6	2280·1	2080·3	1·015
5	147·7	300·4	206·5	1995·3	2285·8	2080·9	1·025
7	148·6	283·2	200·0	1997·9	2250·5	2075·4	1·013
8	148·5	304·1	199·8	1996·7	2293·0	2069·4	1·024
10	148·6	290·7	193·5	1997·1	2264·7	2060·3	1·001
11	148·7	300·4	210·4	1996·8	2284·9	2092·2	1·013
15	148·6	297·8	197·3	1996·9	2280·1	2068·4	1·017
16	149·3	306·7	211·9	1999·9	2295·0	2088·4	1·019
17	148·7	279·0	208·5	1998·7	2245·4	2081·0	1·018
19	148·4	313·9	204·1	1997·3	2285·9	2072·5	1·015
21	148·7	288·1	223·6	1999·3	2237·9	2105·2	1·007
Mean	148·6	297·6	204·2	1997·9	2275·2	2077·6	1·017
SD	0·43	9·9	8·8	1·5	19·2	13·3	0·011
Males							
2	149·0	316·8	228·7	1998·3	2319·5	2112·0	1·031
6	148·9	306·0	225·3	1997·9	2294·6	2107·4	1·028
9	149·7	304·3	227·1	2000·8	2290·0	2118·9	1·006
12	149·0	314·5	229·6	1996·3	2311·5	2115·0	1·025
13	149·0	297·4	214·7	1997·8	2277·4	2092·4	1·012
14	148·9	296·1	216·4	1996·9	2275·2	2098·9	1·021
18	148·6	327·9	233·5	1997·8	2335·2	2121·5	1·018
20	151·8	316·1	226·9	2004·1	2288·2	2099·4	1·020
Mean	149·4	309·9	225·3	1998·7	2299·0	2108·2	1·020
SD	1·0	10·9	6·5	2·5	21·2	10·5	0·008

$D_H:D_O$, dilution space ratio.
* For details of subjects and procedures, see pp. 320–322.

Resting metabolic rate

Subjects were measured either at our laboratory (*n* 13) or at home (*n* 7). There were no differences in health status between individuals measured at home and in the laboratory respectively. Standardised conditions for measurements of BMR were not possible to maintain (Shetty *et al*. 1996), since it was not possible to have the subjects in fasting conditions staying overnight at the laboratory. RMR was measured using a ventilated-hood system. The equipment used at the laboratory was Medical Graphics Model 750013-001 (Spiropharma, Cardiopulmonary Diagnostics A/S, St Paul, MN, USA; Isbell *et al*. 1991) and for the measurements at home a Deltatrac (Datex, Helsinki, Finland) was used. The devices were compared by conducting repeated measurements in a healthy subject. Calculations were made by determining the flow through the hood and by measuring the O_2 and CO_2 concentrations in the in- and outcoming air. Analysers were calibrated before the session with gas mixtures with known O_2 and CO_2 contents according to the manufacturer's instructions. Air was circulated through the hood by a fan, with the speed individually adjusted (about 500–1000 ml/s). Physical activity was avoided before measurements. After a 30 min rest RMR was measured for 20 min (supine position, awake, with an environmental temperature 22–23°C). The measurement conditions were similar for individuals measured at home and at the laboratory. One individual (no. 3) declined measurement of RMR.

Prediction of BMR

BMR was predicted from FFM and fat mass, and FFM predicted from sex, age, height and BW using the equation of Westerterp *et al*. (1995*a*).

$$\text{BMR (MJ/d)} = 0{\cdot}102\text{FFM (kg)} + 0{\cdot}024\text{FM (kg)} + 0{\cdot}85 \quad (n\ 190),$$

where FM is fat mass

For females

$$\text{FFM (kg)} = -12{\cdot}47 - 0{\cdot}074\ \text{age (years)} + 27{\cdot}392\ \text{height (m)} + 0{\cdot}218\text{BW (kg)}\ (n\ 105),$$

For males

$$\text{FFM (kg)} = -18{\cdot}36 - 0{\cdot}105\ \text{age (years)} + 34{\cdot}009\ \text{height (m)} + 0{\cdot}292\text{BW (kg)}\ (n\ 35).$$

Determination of activity energy expenditure and physical activity level

'Measured' AEE was derived by subtracting measured RMR from TEE and predicted AEE was derived by subtracting predicted BMR from TEE.

'Measured' PAL was defined as TEE/RMR and predicted PAL was defined as TEE/BMR.

Body composition

BW was measured to the nearest 0·1 kg using an electronic scale with the subject wearing light clothing without shoes. Body height was recorded to the nearest 1 cm barefoot using a wall-mounted stadiometer. TBW was estimated from single-frequency whole-body bioelectric impedance (BIA), using BIA-101 equipment (RJL System Inc., Detroit, MI, USA).

TBW was also measured from DLW as the dilution space of the loading dose of $^{2}H_2O$ determined at the second voiding, on the following d. TBW was calculated as ^{2}H dilution space divided by 1·04.

FFM was calculated on the assumption that the proportion of water in FFM is 0·732. Body fat was calculated as BW – FFM. Table 1 gives the calculated body composition of each subject.

Statistical methods

Results are presented as means and standard deviations unless otherwise specified. The components of EE were standardised for FFM using linear regression analysis (Ravussin & Bogardus, 1989). Means were compared using Student's *t* test for paired or unpaired samples where appropriate. $P \leq 0{\cdot}05$ was considered significant. Calculations were made using SPSS for Windows version 7.5 (SPSS Inc., Chicago, IL, USA).

Results

Dilution space ratio

Mean dilution space ratio was 1·017 (SD 0·011) in females, 1·020 (SD 0·008) in males and 1·018 (SD 0·010) in the total sample (*n* 21). Individual values are given in Table 2.

Body composition

Mean TBW measured by DLW was 29·5 (SD 5·4) kg in females and 35·6 (SD 4·3) kg in males. Mean TBW measured using BIA was 31·6 (SD 6·4) kg in females and 42·0 (SD 7·4) kg in males. Mean difference between TBW measured by BIA and by DLW was 3·54 (SD 3·6) kg ($P =$ 0·0002). Mean FFM and fat mass measured using DLW was respectively 40·4 (SD 7·3) and 20·8 (SD 8·0) kg in females and 48·8 (SD 5·9) and 18·3 (SD 4·7) kg in males. Mean FFM and fat mass measured by BIA was respectively 43·3 (SD 8·8) and 17·9 (SD 8·8) kg in females and 57·6 (SD 10·2) and 9·6 (SD 7·6) kg in males. Individual values are given in Table 1.

Measured resting metabolic rate and predicted BMR

Predicted BMR averaged 5·24 (SD 0·60) MJ/d in females (*n* 13) and 6·29 (SD 0·38) MJ/d in males. Measured RMR averaged 5·36 (SD 0·71) MJ/d in females (*n* 12) and 6·09 (SD 0·91) MJ/d in males. Individual values are given in Table 3. The difference between measured RMR and predicted BMR (*n* 20) was 0·016 (SD 0·86) MJ/d (NS). However, the difference between measured RMR and predicted BMR was –0·61 (SD 0·79) MJ/d for individuals measured at home (*n* 7) and 0·30 (SD 0·73) MJ/d at the laboratory (*n* 13). In both cases, the difference was not significantly different from zero, but the difference between the groups was significant ($P < 0{\cdot}01$).

Table 3. Total energy expenditure (TEE), measured resting metabolic rate (RMR), activity energy expenditure (AEE) and physical activity level (PAL) values for free-living Swedish subjects aged 91–96*

Subject no.	TEE (MJ/d)	AEE (MJ/d)	RMR (MJ/d)	PAL†
Females				
1	6·65	1·38	5·27	1·26
3	6·12	–	–	–
4	5·16	0·43	4·73	1·09
5	6·51	–0·37	6·88	0·95
7	6·18	0·31	5·87	1·05
8	6·00	0·41	5·59	1·07
10	6·06	0·37	5·69	1·06
11	4·81	0·56	4·25	1·13
15	6·99	2·46	4·53	1·54
16	6·43	1·61	4·82	1·34
17	8·14	2·83	5·31	1·53
19	6·24	0·44	5·80	1·08
21	6·56	0·92	5·64	1·16
Mean	6·30	0·95	5·36	1·19
SD	0·81	0·95	0·71	0·19
Males				
2	7·74	2·54	5·20	1·49
6	9·08	2·03	7·05	1·29
9	7·51	0·11	7·62	0·99
12	7·37	1·94	5·43	1·36
13	7·66	2·12	5·54	1·38
14	9·12	3·13	5·99	1·52
18	7·66	1·02	6·64	1·15
20	8·67	3·40	5·27	1·65
Mean	8·10	2·02	6·09	1·36
SD	0·73	1·13	0·91	0·21

* For details of subjects and procedures, see pp. 320–322.
† TEE/RMR.

Energy expenditure

TEE averaged 6·3 (SD 0·81) MJ/d in females and 8·1 (SD 0·73) MJ/d in males (Table 3).

Activity energy expenditure and physical activity level

Measured AEE averaged 0·95 (SD 0·95) MJ/d in females (*n* 12) and 2·02 (SD 1·13) MJ/d in males (Table 3). Predicted AEE averaged 1·05 (SD 0·84) MJ/d in females and 1·81 (SD 0·56) MJ/d in males. Relative to TEE, measured AEE comprised 14·2 % and predicted AEE 16 % in females. In males measured AEE was 24·4 and predicted AEE 22·0 % TEE.

Measured PAL averaged 1·19 (SD 0·19) in females and tended to be higher in males (1·36 (SD 0·21), $P = 0{\cdot}08$; Table 3). Predicted PAL averaged 1·24 (SD 0·17) in females and 1·40 (SD 0·10) in males.

Discussion

This study attempted to characterise EE and its components in free-living, comparatively healthy, very old people. We hypothesised that both BMR and PAL, and thus TEE, would decline with advancing age. Our main finding is that in this group of people living to a very old age, PAL tends to be very low, but that RMR is not substantially different from that of individuals aged 70–80 years. To our knowledge these data are the first describing TEE determined by the DLW technique and its components in this age-group.

Resting metabolic rate

A difference was found according to whether the individuals were measured at home or at the laboratory, with higher values in the group measured at the laboratory. It is conceivable that these very old people had difficulties in completely relaxing in the laboratory setting. Thus, the RMR data obtained at the laboratory may overestimate true values, thus tending to underestimate AEE and PAL values.

Study results

In general EE seems to decrease with advancing age. This situation could be due to decreases in BMR as well as AEE. The main determinant of BMR is FFM (Shock *et al*. 1963), and thus loss of FFM with age is a major factor in the reduction of BMR (Shock *et al*. 1963; Roberts *et al*. 1995). Whether the metabolic activity within FFM also is lower in the elderly is debatable (Piers *et al*. 1998). A reduction in PAL is another major factor in the decrease in EE with advancing age (Roberts *et al*. 1995; Black *et al*. 1996). However, there are still limited data on PAL in the elderly.

A comparison of TEE measured by DLW in young and elderly males have shown that the decrease in BMR accounted for 36 % and AEE 64 % of the lower TEE in the elderly (Roberts *et al*. 1995). When comparing the present study population with a sample of 73-year-old subjects (Rothenberg *et al*. 1998) TEE, PAL and AEE were lower in the 91–96-year-old subjects, while RMR did not differ between age-groups. TEE was 34·4% lower in the older females compared with the younger females, and for males the difference was 24·6 %. RMR was 4·8 % lower in the older females; for males the difference was 2·1 %. The difference in AEE between the older and younger females was 76·2 % and for males 55·8 %. AEE constituted 41 % TEE in females and 42 % TEE in males aged 73 years old compared with 22 and 23 % respectively in females and males aged 91–96 years old. When comparing with another age-group in another population there are difficulties relating to differences in physical activity and state of health. In such small samples as those in the study of 73-year-old subjects (*n* 12) Rothenberg *et al*. 1998; and the present study (*n* 21), personal choice and individuality also play an important role and limit generalisability.

Age remains a negative predictor when TEE is expressed as PAL (Black *et al*. 1996), but TEE and PAL vary widely, ranging from physically active, recently retired subjects to frail and chair-bound subjects (Black *et al*. 1996). The relationship between PAL and AEE may be altered in the elderly (Black *et al*. 1996). High PAL values could be explained by relatively lower values for BMR compared with those of younger individuals (Black *et al*. 1996). In the present study PAL values indicate very low physical activity in the 91–96-year-old subjects but small differences in RMR compared with the younger sample. In the study of 73-year-old subjects (Rothenberg *et al*. 1998) the PAL value of females was 1·78 and of males 1·62, indicating an active lifestyle for the age-group.

When RMR was adjusted for FFM there were no differences between sexes nor between age-groups. Piers *et al*. (1998) found that BMR of older individuals was significantly lower than that of younger ones, even after accounting for differences in the composition of FFM. The subjects in their study were men only, and both the young and elderly group were markedly younger than those in the present study, which make the studies not entirely comparable. In the present study the different components of FFM were not investigated separately. However, for TEE and AEE there was a marked difference according to age, indicating that the older group used very limited amounts of energy for physical activity, especially when considering that diet-induced thermogenesis is included in our estimate of AEE.

Conclusions

In this sample of very old individuals TEE, AEE and PAL were lower, while RMR was not substantially different from that of another group of younger elderly. Values for TEE, AEE and PAL indicate that these individuals have very limited physical activity.

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